Columbia University in the City of New York

LAMONT GEOLOGICAL OBSERVATORY
PALISADES, NEW YORK

DYE DIFFUSION EXPERIMENTS ON THE GREAT BAHAMA BANK

Prepared by: Michael Costin

Technical Report No. CU-6-63 to the Atomic Energy Commission
Contract AT(30-1)2663

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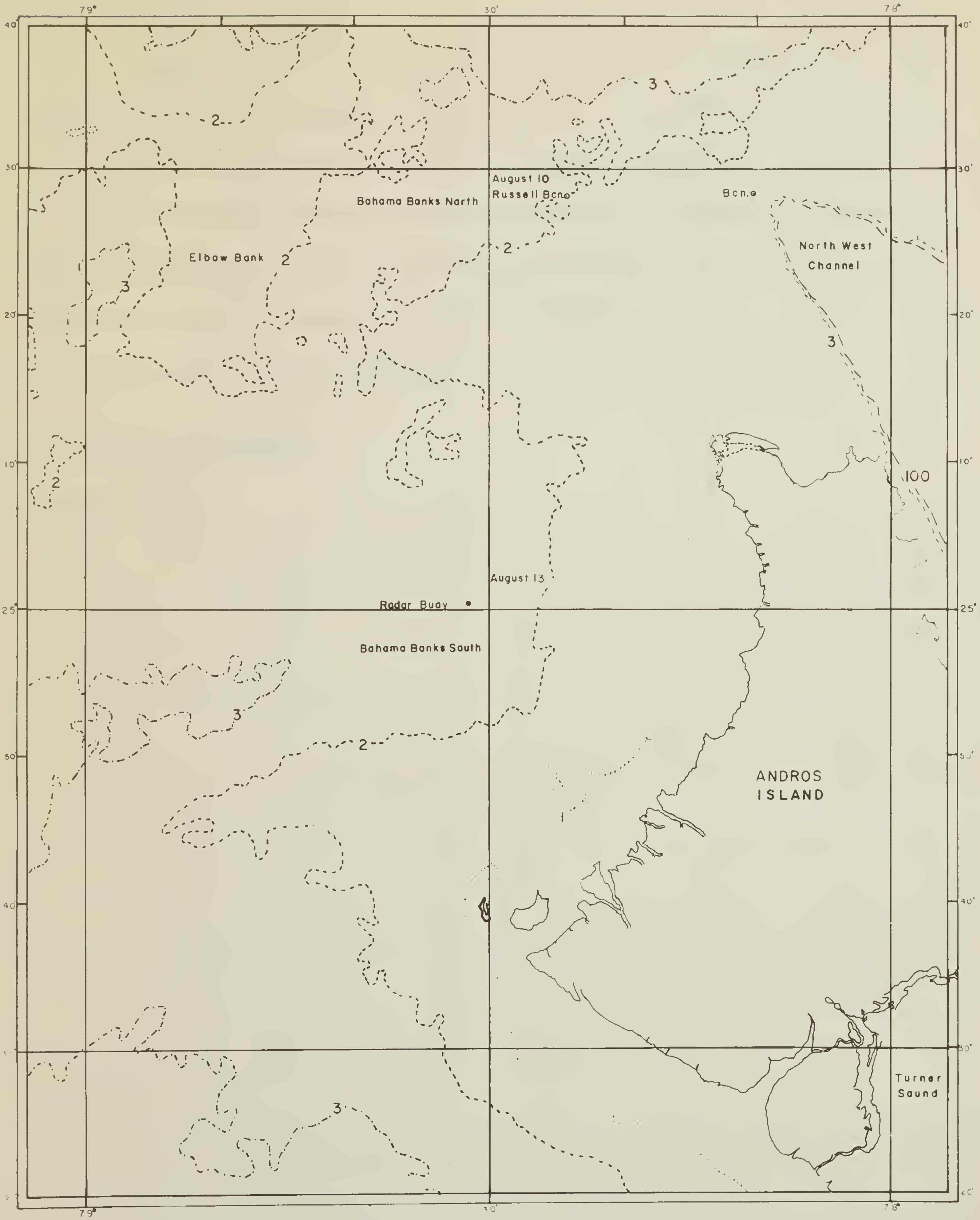
INTRODUCTION

Precise observations of the effects of turbulent diffusion on artificial tracers in natural environments are made difficult by the rapid rate of change of the measurable characteristics of the tracer compared to the time necessary to complete a survey. Ideally, tracer studies in shallow water where conditions of reduced wind and current velocities prevail would facilitate the observation and interpretation of these turbulent mechanisms.

This paper describes two dye diffusion experiments conducted on the Great Bahama Bank during August, 1962. Rhodamine B dye was dumped in the surface waters in each of two locations designated as Bahama Banks North (BBN) and South (BBS) on August 10 and 13, respectively (Figure 1).

This work was done to complement studies of marine sedimentation in the area and to gain some understanding of the circulation and turbulence characteristics in shallow tidal areas. Furthermore, this study was made to provide data on turbulent mixing which could be compared to similar work done off the New Jersey coast (Costin, Davis, Gerard and Katz, 1963, cited as ENY) and in an open ocean area north of the Bahamas (in preparation).

Dye concentration was measured continuously at mid-depth only. The vertical distribution of concentration was not measured for the following reasons: (1) this experiment was devoted to the study of horizontal diffusion by turbulence, since effects of the vertical diffusion process may be measured rather easily by other methods (for instance, from vertical profiles of velocity or temperature); (2) the water in the experimental areas is uniformly shallow (2 1/4 to 2 1/2 fathoms) and there is no stratification, as demonstrated by the lack of both horizontal and vertical temperature gradients. Thus, dye concentration is almost uniform vertically except in the boundary layer near the bottom. Figure 12, an aerial photograph taken 45 minutes after a dump (BBS)



Location of dye dumps on the Great Bahama Bank - August, 1962

depth in fathoms

FIGURE 1

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https://archive.org/details/dyediffusionexpe00cost

shows the surface (light colored) layer of dye drifting over the darker dye, which is nearer the bottom. This distortion of the dye patch is due to differential velocities induced by bottom drag. It is evident that, as the tide turns, the shearing force would be in the opposite direction. However, because of rather thorough vertical mixing (as evidenced by the lack of vertical stratification), the distortion of bottom drag is included in the horizontal dye measurements over the range of a tidal excursion and must be considered small, at a given moment, when compared to the enlarging size of a patch.

EXPERIMENTAL TECHNIQUES

Sampling System

The research vessel LORD RAYLEIGH was outfitted with a stationary sampling pipe which extended below and in front of the bow wake. Samples from one fathom were continuously pumped through the cuvet of the fluorometer by a positive displacement rotary pump mounted on the deck. It has been found that the presence of bubbles in the cuvet changes the fluorescent readings by varying amounts and renders the record nearly useless. By means of an in-line flowmeter and gate valves at the pump and in the outlet line of the fluorometer, the rate of flow could be regulated throughout the sampling system, and the formation of bubbles was not a problem. A standard Turner fluorometer, model 111, modified with a continuous-flow cuvet, with the same filters and operating characteristics as described in ENY, was used to measure the dye concentration.

Navigation

Each illustration of concentration contours, as Figure 3, represents a set of sampling runs (indicated by arrows) made at various intervals after introduction of dye into the surface waters. These sets were completed in as short a time as possible in order to exclude gross advective and diffusive distortion when reconstructing experimental events, while including enough crossings to

adequately construct the concentration contours. In BBN five sets of crossings were made, each set averaging 1.92 hours and consisting of about 10 crossings. In BBS seven sets were completed with an average time of 1.38 hours for 11 crossings per set.

With the use of a variable range-marker radar, ship's positions were fixed relative to a stationary radar target (BBN - Russell Beacon, BBS - an anchored radar reflector buoy, Figure 1) at the beginning and end of each sampling run. These position-time marks were entered manually on the continuous chart recording of the fluorometer output. At the beginning of each new set of crossings, attempts were made to determine the position of the center of high concentration and the lengths of the long and short axes of the patch. Additional sampling runs were then made to fill in the concentration isolines.

Meteorological Data and Miscellaneous Observations

Estimations of sea state and prevailing wind conditions were made by visual observation from the research vessel. The meteorological data were verified and supplemented by records from weather stations at Middle Bight on Andros, Nassau, Miami, and on Grand Bahama Island.

Aerial Photography

The same general equipment as described in ENY was used in the aerial coverage of the experiments on the Bahama Banks. In morning and afternoon flights the plane was able to remain over the dye patch for about six hours per day. During that time photographs were taken about every ten minutes from altitudes ranging from 500 to 3500 feet, depending on the size of the patch. Because of the extreme clarity of the water and the light-colored bottom, it was nearly impossible to obtain good black and white exposures with the 23A and 73 Wratten filters. These filters have the effect of making the dye patch appear light in a dark background. A 77A Kodak Wratten filter in B-glass (passing most of the

red and green, but blocking 570 to 595 mu, or the emission spectrum of Rhodamine B) made the dye appear dark in the light surrounding waters. As a result, definitive patch outlines were obtained at the expense of some detailed fine structure. Good color photographs were taken with the use of standard haze and polaroid filters.

GENERAL CIRCULATION IN THE EXPERIMENTAL AREAS

Previous reports (Smith, 1940 and the West Indies Pilot) have indicated that the water movements over and around the Bahama Banks tend to be complex due to the proximity of the deep ocean channels and the shallow water surrounding the neighboring land masses. In general, the current system in the channels is characterized by a westerly drift at mid-depth (Cook, 1963) that is closely bound up with the currents forming the sources of the Gulf Stream. Surface currents in the channels are usually weak, variable, and locally dependent on the wind.

The distribution of isohalines on the Great Bahama Bank (Smith, 1940) suggests that water motions are controlled largely by the wind. High salinity water (37 to 43 o/oo in the summer, 35 to 38 o/oo in the winter), formed by evaporation on the bank and tidal exchange with high salinity lakes on Andros Island, moves northwestward under the influence of southeasterly winds in the summer months and is pushed back towards Andros in the winter, as evidenced by the inflow of lower salinity ocean water. The tidal flow near the edge of the bank tends to be nearly perpendicular to the 100-fathom line with an average velocity of about one knot. Smith indicates that in the central portion of the bank the tidal streams meet and produce a resultant flow, the ebb to the northwest and the flood to the southeast, with magnitude dependent on seasonal wind variation.

EXPERIMENTS

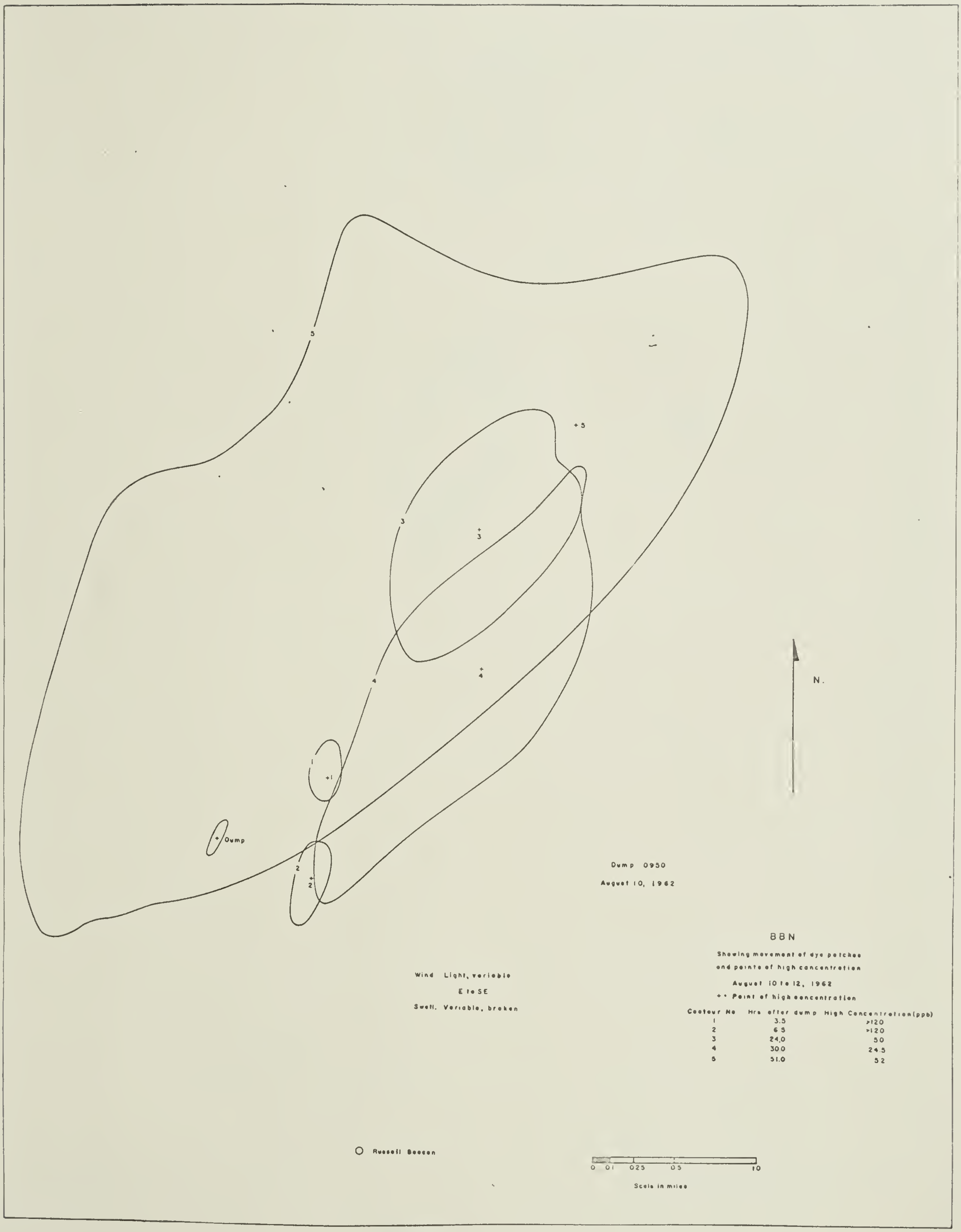
August 10, 1962 - EBN

On this date 1.44 x 10^5 gm. of Rhodamine B dye was introduced into the surface waters at 0950 just north of Russell Beacon (Figure 1). The bottom in this area is flat and covered by grassy patches and isolated coral formations. Figure 2 shows the relative motions of the patch and the approximate center of high concentration until 1200, August 12, 51 hours after introduction. During this time the sea surface was characterized by intermittent periods of calm and a light choppy swell. The wind was light and variable, from the east and northeast with rain squalls on the first day, shifting slowly to the southeast toward the end of the survey. The motion of the patch (Figure 2) is indicative of a tidal oscillation with major axes running NE-SW and the greatest velocities (about 0.5 knots) in the direction of the ebb. There is also a permanent drift to the northeast with a velocity of about 0.07 knots.

During the early hours of the survey, when the wind was unsteady, the patch elongated generally in a direction parallel to the axis of the tidal ellipse (Figures 2, 3, 4). As the wind steadied in the southeast, there was a tendency for the patch to spread in a direction parallel to the wind (Figure 5). During these later hours fingerlike striations of dye formed at the leading and trailing edges of the patch (Figure 6, an aerial photograph taken 25 hours after dump) parallel to the troughs of the swell, which was advancing to the northeast.

August 13, 1962 - BBS

At 0910, 1.26 x 10^5 gm. of Rhodamine B dye was dumped north of the radar buoy shown in Figure 1. The bottom in this area consists of fine calcareous marl and is flat and smooth. Except for calm during the night and early morning hours, the wind was southeasterly at about 3 to 5 knots, with reduced velocities on the last day. Motion in this area (Figure 7) is characteristic of a tidal



BBN

Showing movement of dye patches
and points of high concentration

August 10 to 12, 1962

+ • Point of high concentration

Contour No	Hrs after dump	High Concentration(ppb)
1	3.5	>120
2	6.5	>120
3	24.0	50
4	30.0	24.5
5	51.0	52

FIGURE 2

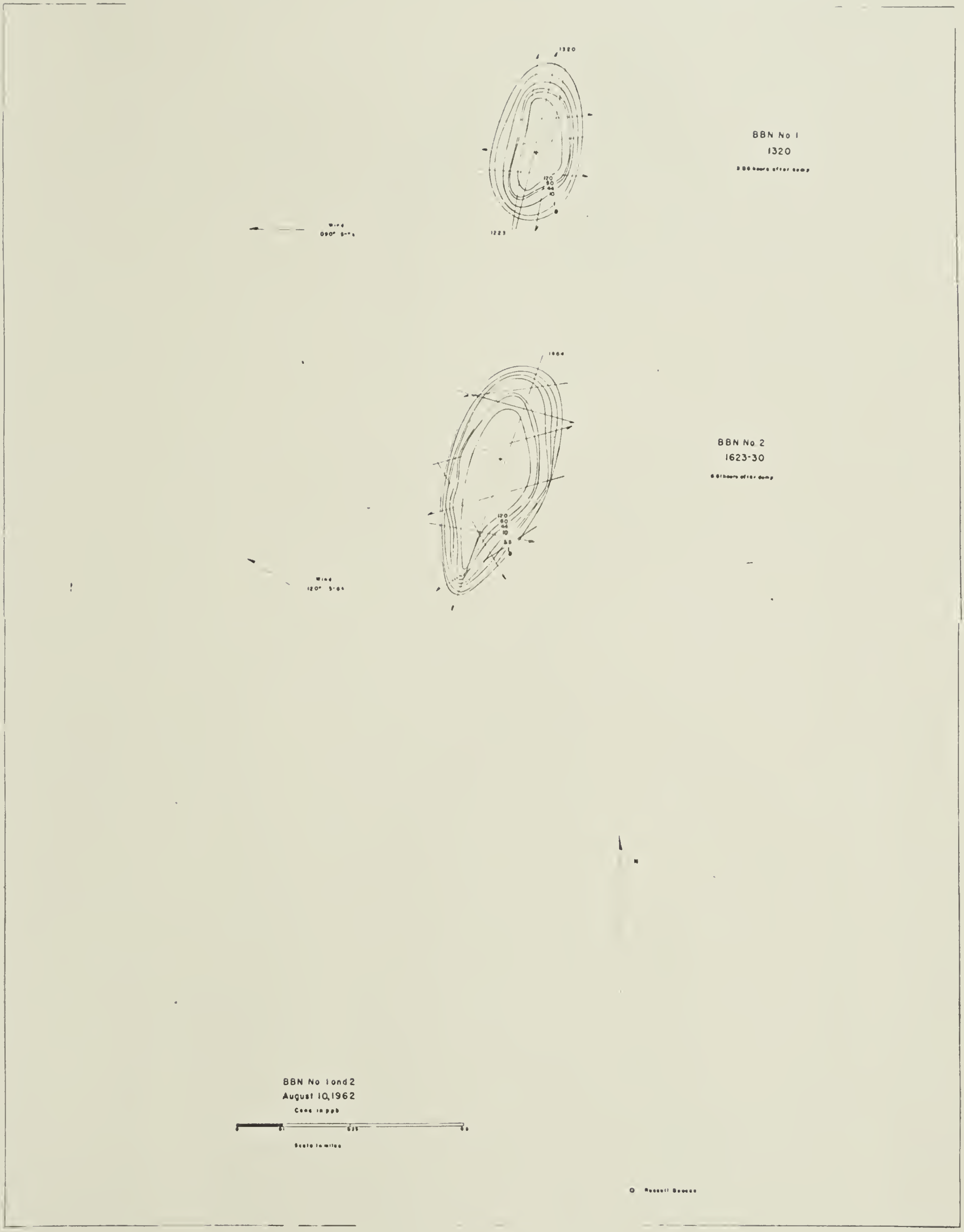

1320
120
80
44
10
Wind
BBN No 1
1320
120
80
44
10
Wind
BBN No 2
1623-30
BBN No 1 and 2
August 10, 1962
Conc in ppb
Scale in miles

FIGURE 3

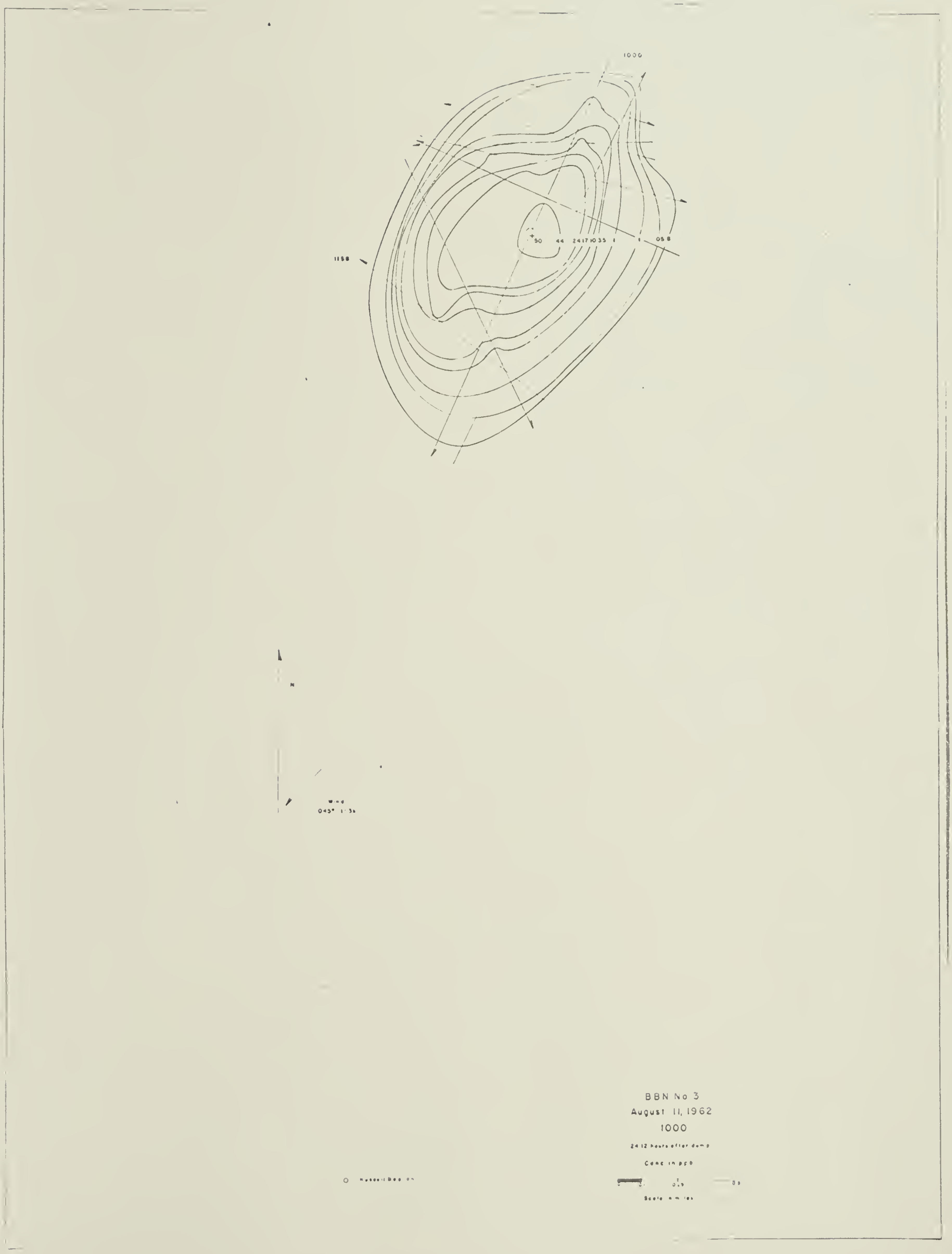

1000
1158
50
44
24
17
10
3 5
1
1
05
N
Wind
045°
BBN No 3
August 11, 1962
1000
24.12 hours after dump
Conc in ppb
Scale n miles

FIGURE 4

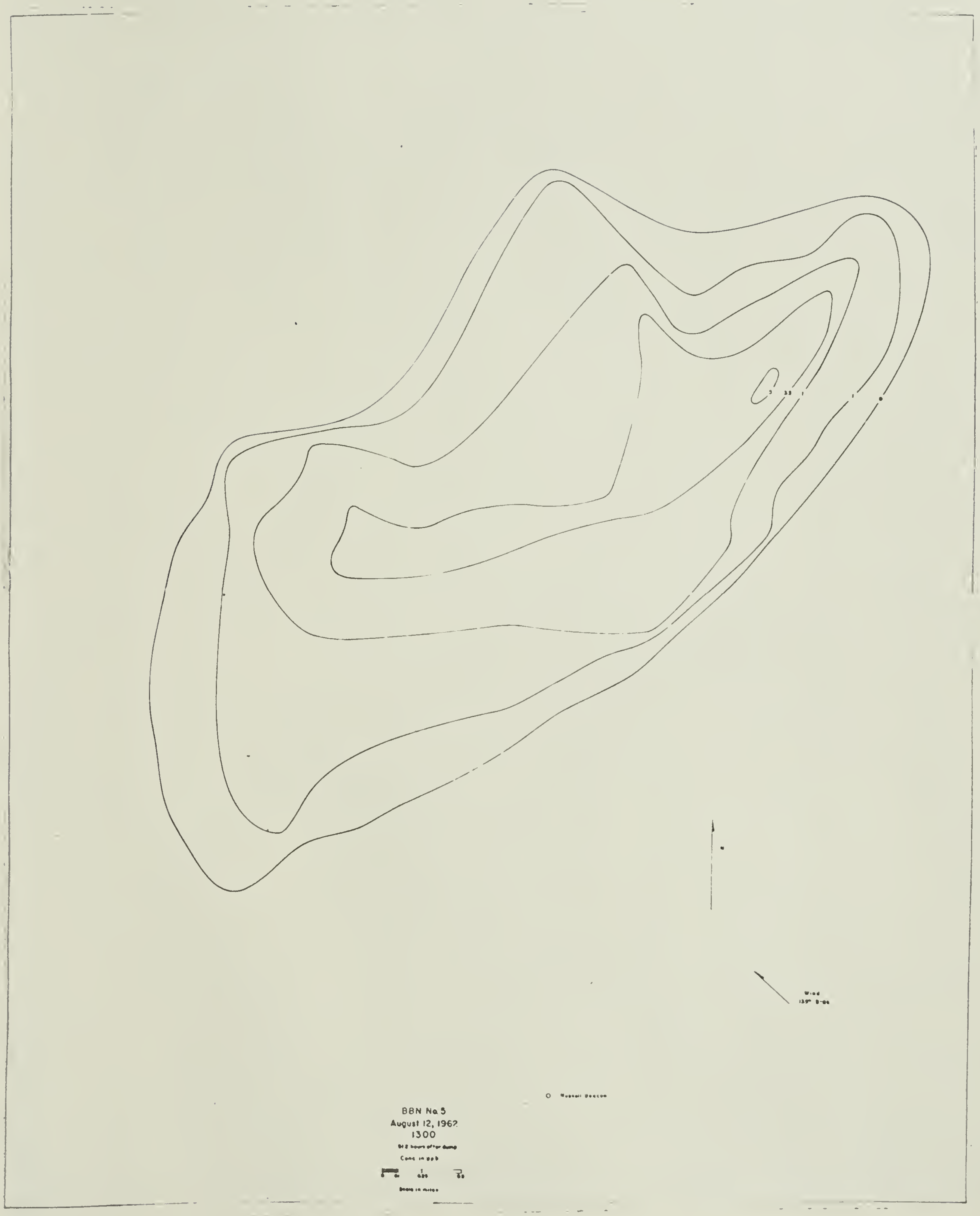

5
1
1
Wind
BBN No 5
August 12, 1962
1300
Conc in ppb
Scale in miles

FIGURE 5

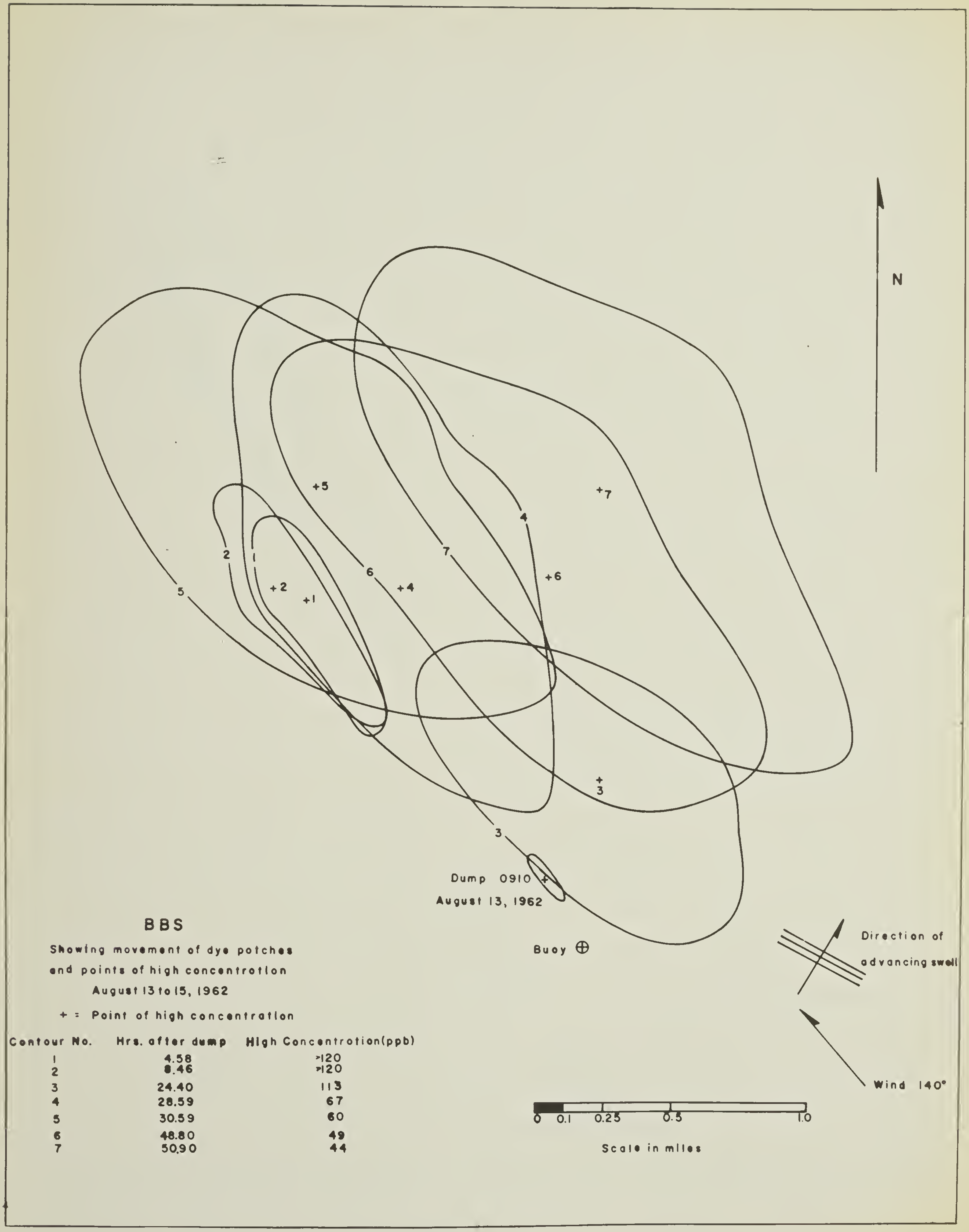
ellipse with a major axis trending NW-SE and the greatest velocities (0.25 knots) in the direction of the ebb. There is a permanent drift to the northeast with a velocity of about 0.03 knots. Figures 8 through 11, plotted on a larger scale, illustrate the elongation of the dye patch in the direction of the tidal ellipse. Unlike BBN, the flow in this area is roughly parallel to the wind, and it may be assumed that in the central regions of the bank, where tidal velocities are reduced, the effects of wind on the general circulatory pattern are more pronounced.

As the shape of the patch changed from a flattened ellipse (Figures 8 and 12, one hour 50 minutes after dump) to a more oval shape (Figures 11 and 13, 31 hours after dump), striated patterns developed in the leading and trailing edges of the patch. Unlike BBN, the striations persisted throughout the survey, but retained the same general orientation parallel to the swell. As indicated above, the winds in BBS were light and steady during the daylight hours, and the swell was a generally stable feature with the crests advancing from SW to NE (Figure 7), due to refraction around shallow flats, which extend out about ten miles from the western shore of Andros.

COMPARISON AND SUMMARY OF EXPERIMENTS

The respective motions of the two dye patches (Figures 2 and 7) tend to agree with drifts reported by Smith (see General Circulation, above). Circulatory trajectories of the center of the dye patches are due to tidal currents; tidal ellipses with major axes at right angles to the 100-fathom line near the edge of the bank and trending NW-SE on the central regions. These oscillatory tidal currents are superimposed on a residual drift dependent on seasonal wind variation; northerly drift in summer, southerly drift in winter.

The fingerlike striations of dye mentioned above (Figure 13) were also observed in most of the surface dye experiments off the Jersey coast. While the striations are not stable configurations, even when compared to the changing



BBS

Showing movement of dye patches
and points of high concentration
August 13 to 15, 1962

+ = Point of high concentration

Contour No.	Hrs. after dump	High Concentration(ppb)
1	4.58	>120
2	8.46	>120
3	24.40	113
4	28.59	67
5	30.59	60
6	48.80	49
7	50.90	44

FIGURE 7

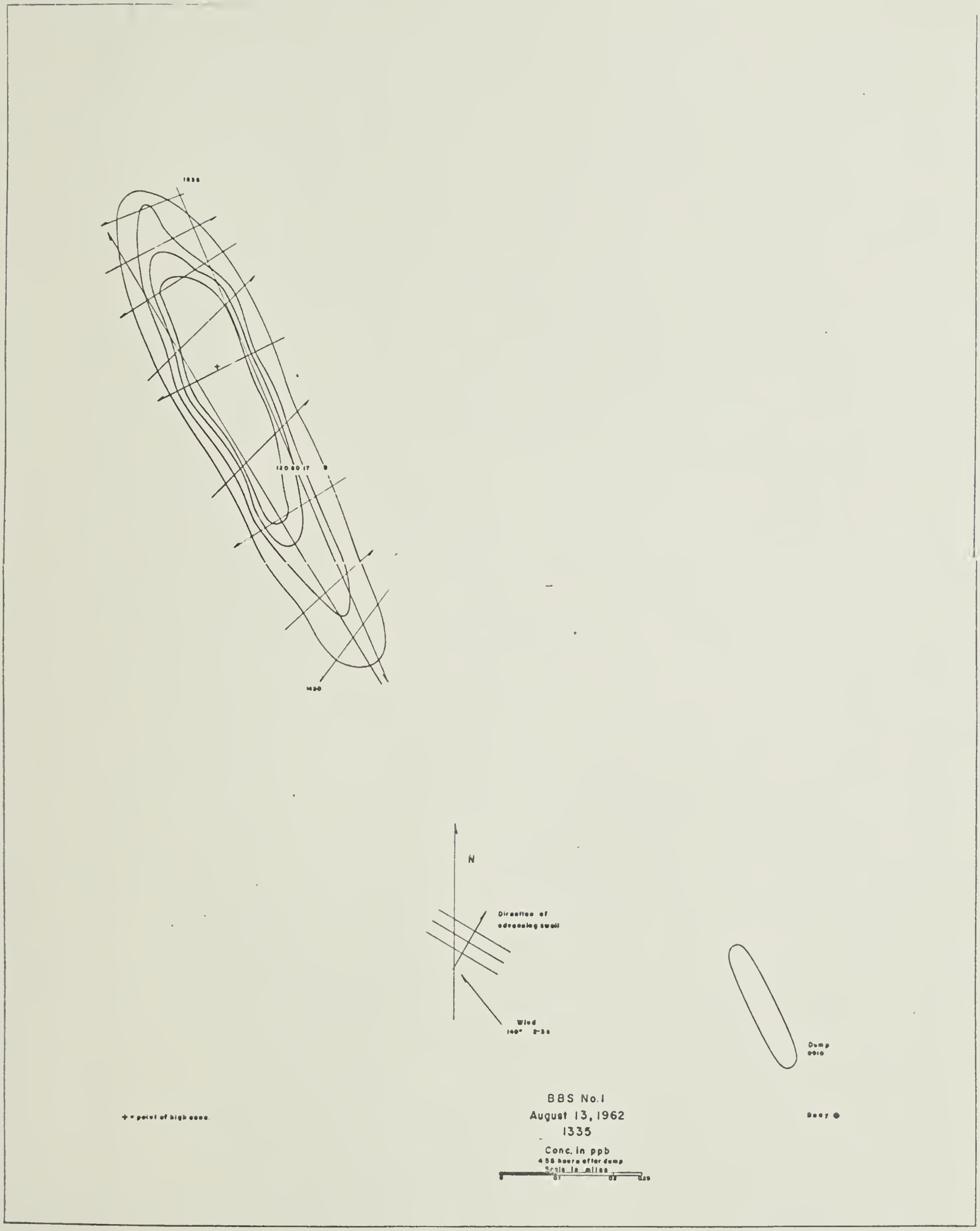

1335
120 80 17 8
1430
N
Direction of advancing swell
Wind
140° 2-3k
Dump
0910
+ = point of high conc.
BBS No. I
August 13, 1962
1335
Buoy ●
Conc. in ppb
4.38 hours after dump
Scale in miles
0
0.1
0.2
0.25

FIGURE 8

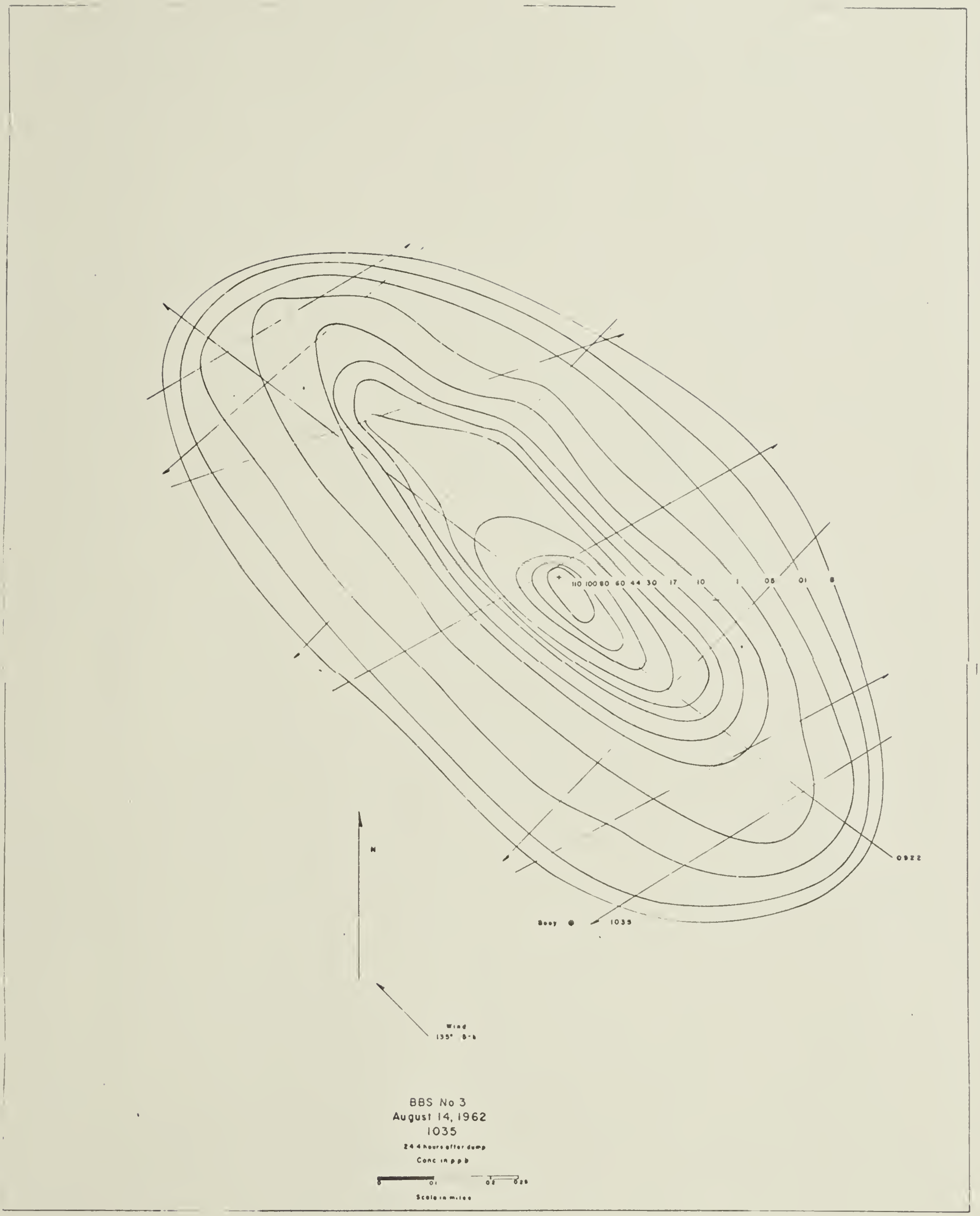

110 100 80 60 44 30 17 10 1 05 01 0
N
0922
Buoy
1035
Wind
135° 8-6
BBS No 3
August 14, 1962
1035
24 4 hours after dump
Conc in ppb
0
01
02
025
Scale in miles

FIGURE 9

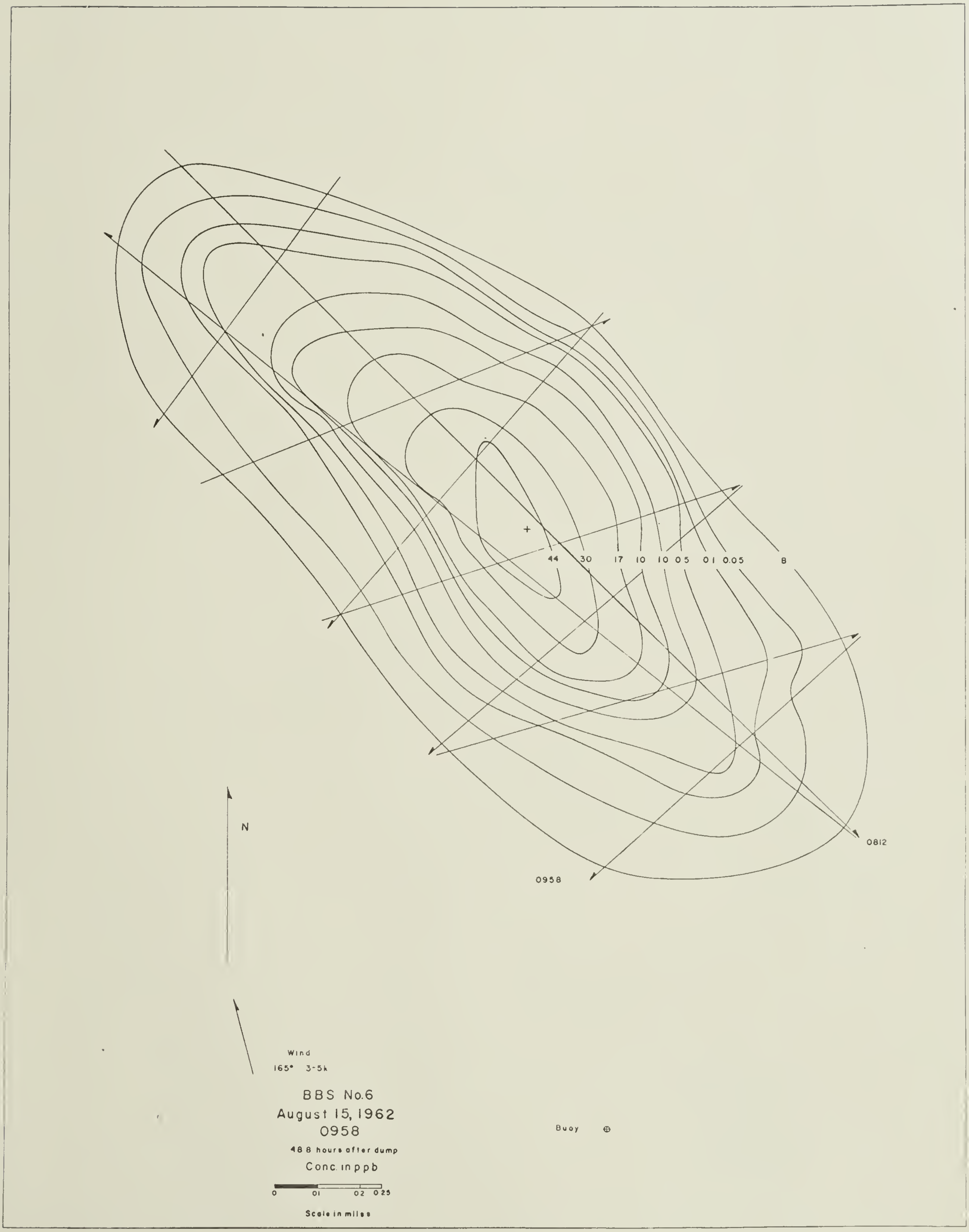
44
30
17
10
10
05
01
0.05
8
0812
0958
N
Wind
165° 3-5k
BBS No.6
August 15, 1962
0958
48 8 hours after dump
Conc. in ppb
0
01
02
025
Scale in miles
Buoy ⊕

FIGURE 10

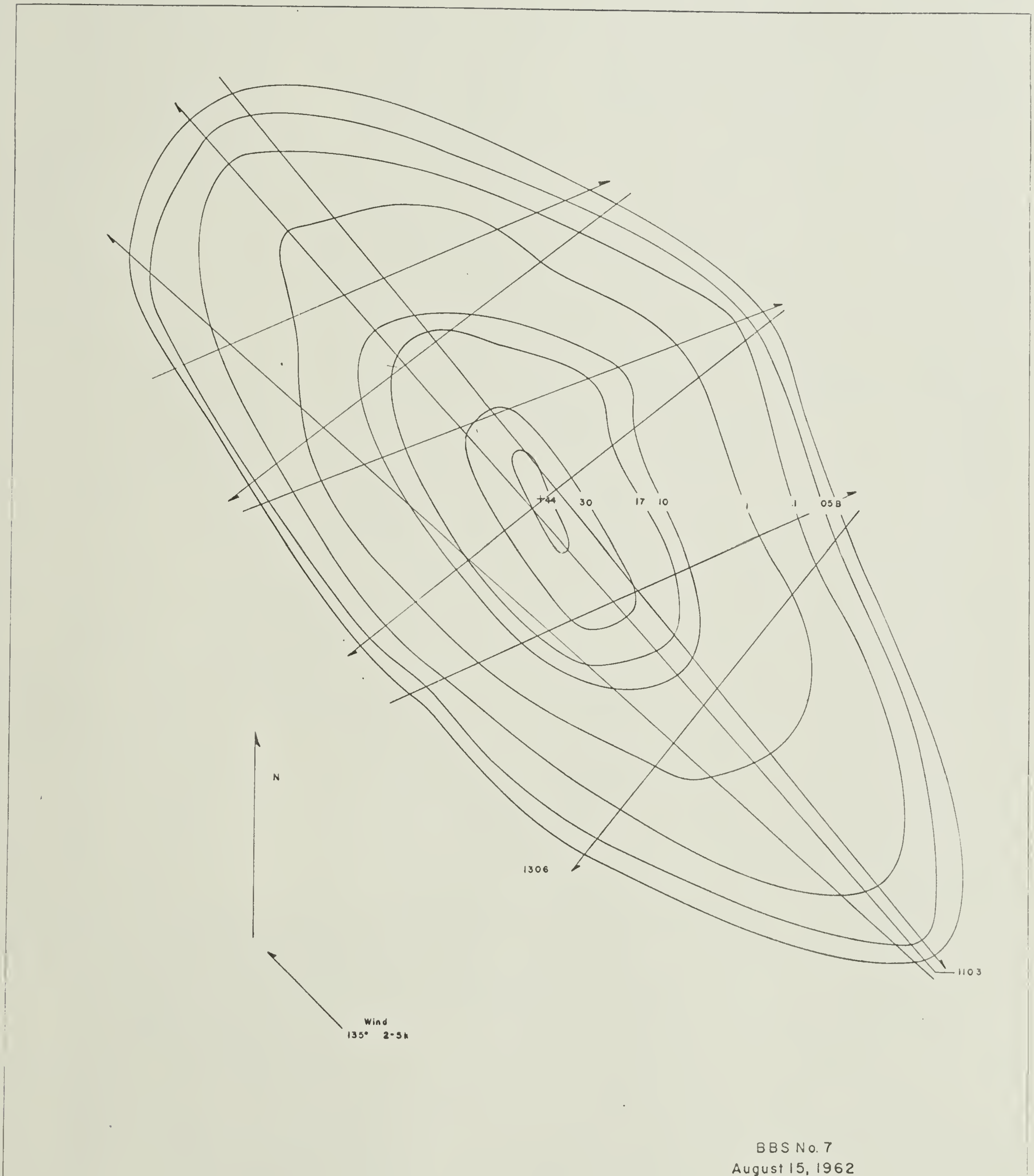

44
30
17
10
1
.1
05
B
1306
1103
N
Wind
135° 2-5k
BBS No. 7
August 15, 1962
1200
50. 9 hours after dump
Conc. in ppb
0
01
02
025
Scale in miles
Buoy ⊕

FIGURE 11

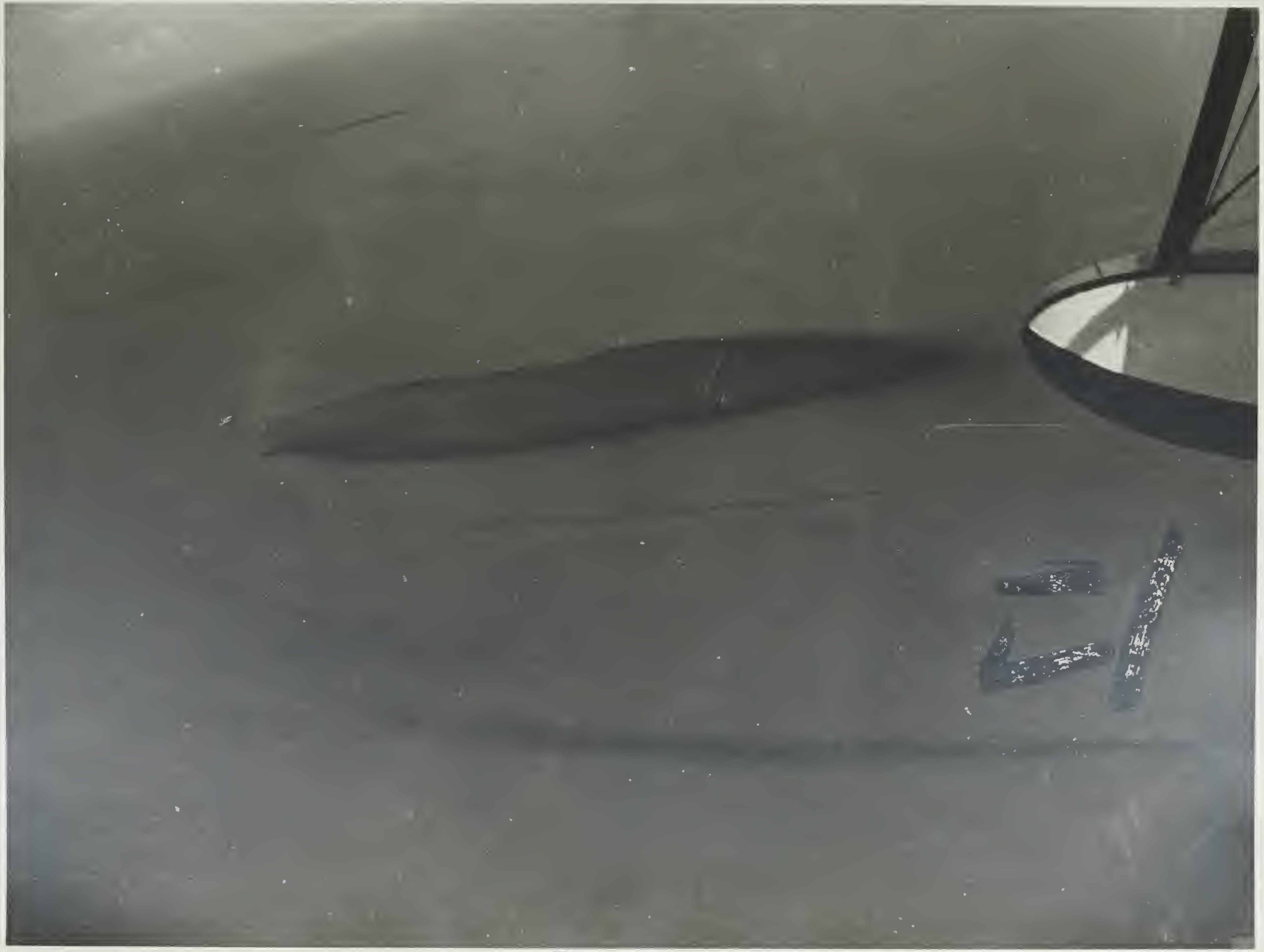


FIGURE 18

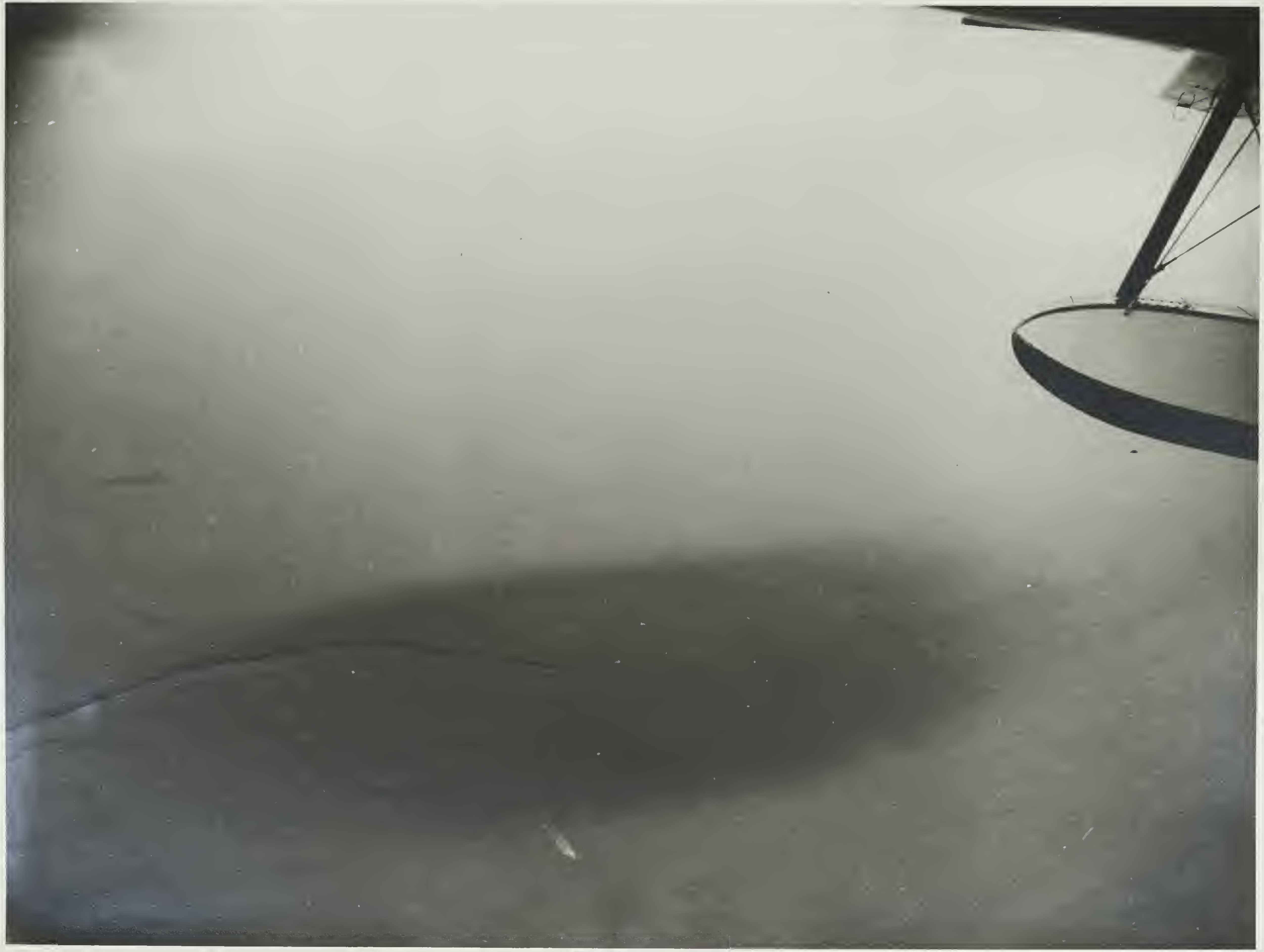


FIGURE 13

shape of a patch, they are generally well oriented parallel to the troughs of the swell and have an apparent formational frequency of some multiple of the wave length. The generation of these features will be more fully treated in following discussions.

The ratio of long to short axes of the two patches (Figure 14) is about 2 (BBS) to 2.4 (BBN), except in the initial stages of diffusion. These are much smaller than the ratios of 6 to 8 obtained in the experiments off the New Jersey coast in 1961-1962 (ENY). Thus, turbulent diffusion on the Bahama Bank can be regarded as more nearly isotropic than that off New Jersey. This is particularly well illustrated by the curves for BBS in Figure 14. The curves point out that the rate of change in the lengths of the long and short axes is nearly identical, except in the period from 25 to 30 hours after dump. The initial displacement of the curves is due to the fact that the dye was dumped in an elongated patch (Figure 7) parallel to the troughs of the swell and retained the original orientation throughout the survey. It is assumed that if the dye in BBS had been introduced in a circular patch, it would have retained that same general shape with only slight elongation in the direction of the wind or tidal ellipse.

In general, the more isotropic diffusion observed on the banks is the result of the shallowness of the water and the greatly reduced wind drift and tidal currents. Off the coast of New Jersey, wind drift and tidal currents (particularly the former) develop into a strong shear flow which diffuses the dye patch more strongly in the direction of the mean flow.

Figure 15 is the graph of the maximum concentration, C_{max}, versus time in seconds after dump. Because of instrumental limitations (fluorometer measures concentration $\leq$ 120 ppb, see Table 1, BBN and BBS) and some uncertainty that C_{max} was accurately measured for a given time after dump, the curves are plotted from only three points. In both of the Bahama experiments C_{max} is roughly pro-

LENGTH OF AXES VS TIME

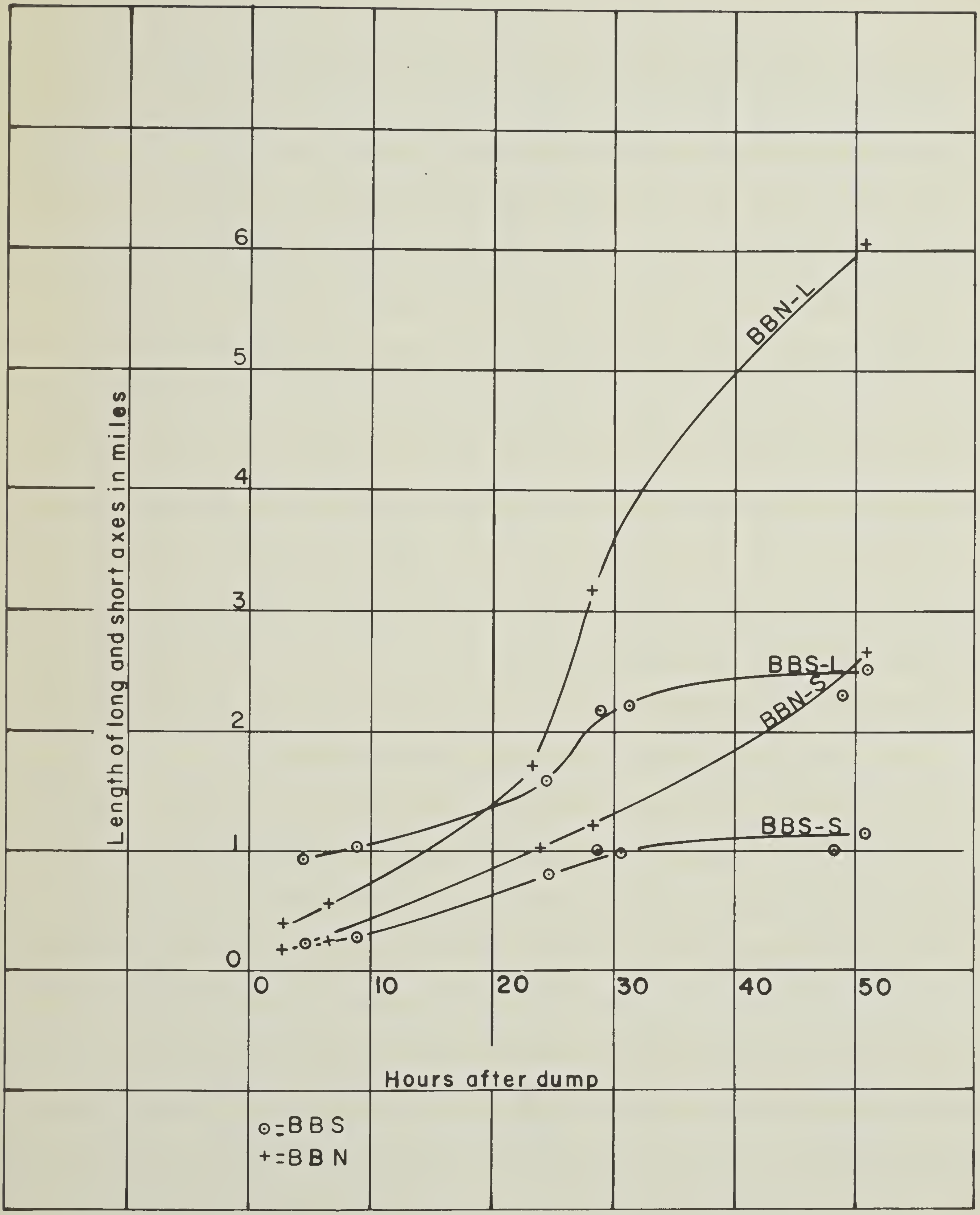
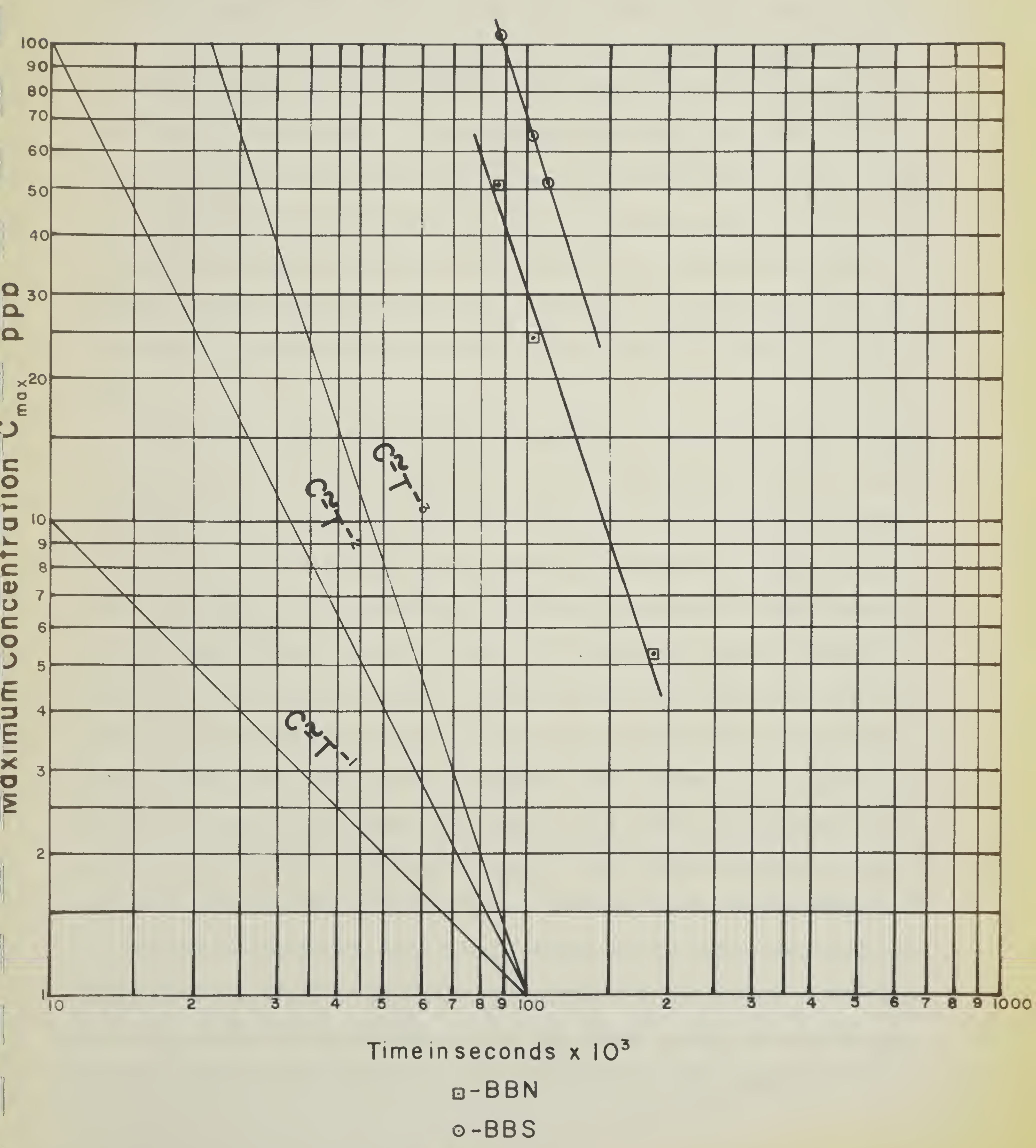


FIGURE 14



Maximum Concentration vs Time

FIGURE 15

portional to the minus 3 power of the time, while in most of the New Jersey experiments $C_{max} \simeq T^{-2.4}$. These values would indicate that the level of turbulence (or rate of energy dissipation ϵ in Kolmogorov's theory, 1941) is higher on the shallow banks than off the coast of New Jersey. However, because of the rapid rate of distortion and the large asymmetrical shapes that obtain off New Jersey, we are even less certain of the accuracy of measurements of C_{max} in that area. Because of the difficulty in making accurate measurements, and since the relationship of C_{max} proportional to some power of the time is derived from theories treating essentially isotropic turbulence, we feel that this relationship is not a reliable guide in the comparison of turbulent parameters in two areas.

Perhaps more useful relationships for comparison of local turbulent effects are the ratio of the area of a given dye patch or concentration contour to the time after dump. At some time after the introduction of dye, the distribution of the tracer can be described by lines of equal concentration. The equivalent radius, $r_e = \sqrt{\frac{A}{2\pi}}$, may be determined from the area enclosed by these concentration isolines. The area of each isoline, and therefore r_e, would be expected to increase at some rate determined by the level of the local turbulence (or ϵ) to a time $t_1 > t_0$, and then decrease for $t > t_1$ (t_1 not the same for each isoline). Change of area and r_e with time are dependent on the mechanism of dye release, especially in the initial stages, the amount of dye dumped, and the level of turbulence in the area. Figures 16 through 19 illustrate relationships of the contour areas versus time and concentration versus r_e for the Bahama experiments.

For ease of comparison, data from the Bahama and New Jersey experiments are tabulated below. The areas in square miles enclosed by the contour of the threshold concentration and also values of C_{max} for various t after dump are listed. The Bahama data is best compared to that of October 31, 1961, which is the only

New Jersey experiment making use of a comparable amount of dye.

TABLE I.

AREAS IN SQUARE MILES ENCLOSED BY CONTOUR OF THRESHOLD CONCENTRATION (Values of C_{max} in ppb)

Experiment	Time in hours after dump 7	10	25	50
ENY, Oct. 17	0.5 sq. mi. (15 ppb)	0.3 sq. mi. (2.7 ppb)		
ENY, Oct. 31		0.7 sq. mi. (22 ppb)	3.0 sq. mi. (1.5 ppb)	
BBN	0.1 sq. mi. (>120 ppb)	0.4 sq. mi. (>120 ppb)	1.5 sq. mi. (50 ppb)	~10.0 sq. mi. (5.2 ppb)
BBS	0.25 sq. mi. (>120 ppb)	0.5 sq. mi. (>120 ppb)	1.2 sq. mi. (113 ppb)	2.0 sq. mi. (49 ppb)

These figures show that the area of the threshold concentration, A_t, of the smallest dump, October 17, was decreasing 10 hours after introduction. A_t of the dump of October 31, containing four times as much dye, increased throughout the first 25 hours after dump, although C_{max} was decreasing rapidly (to 1.5 ppb). At 25 and 50 hours after dump both of the areas of the dye patches on the Bahama Banks were increasing, but at a slower rate than that of October 31, and the concentrations, C_{max}, were still relatively high, particularly that of BBS.

When P, "The most probable diffusion velocity" of Joseph and Sender (1958), is computed, we obtain values of approximately 0.4 cm/sec for BBN and 0.21 cm/sec for BBS. Both of these values are well below the average of 1.0 cm/sec derived from the New Jersey experiments. The higher value of P in BBN is due to increased current velocities and greater shear resulting from the rougher bottom in that area. This and comparison of change of A_t with time for October 31 and Bahama Banks experiments indicate that the level of turbulence is somewhat higher off

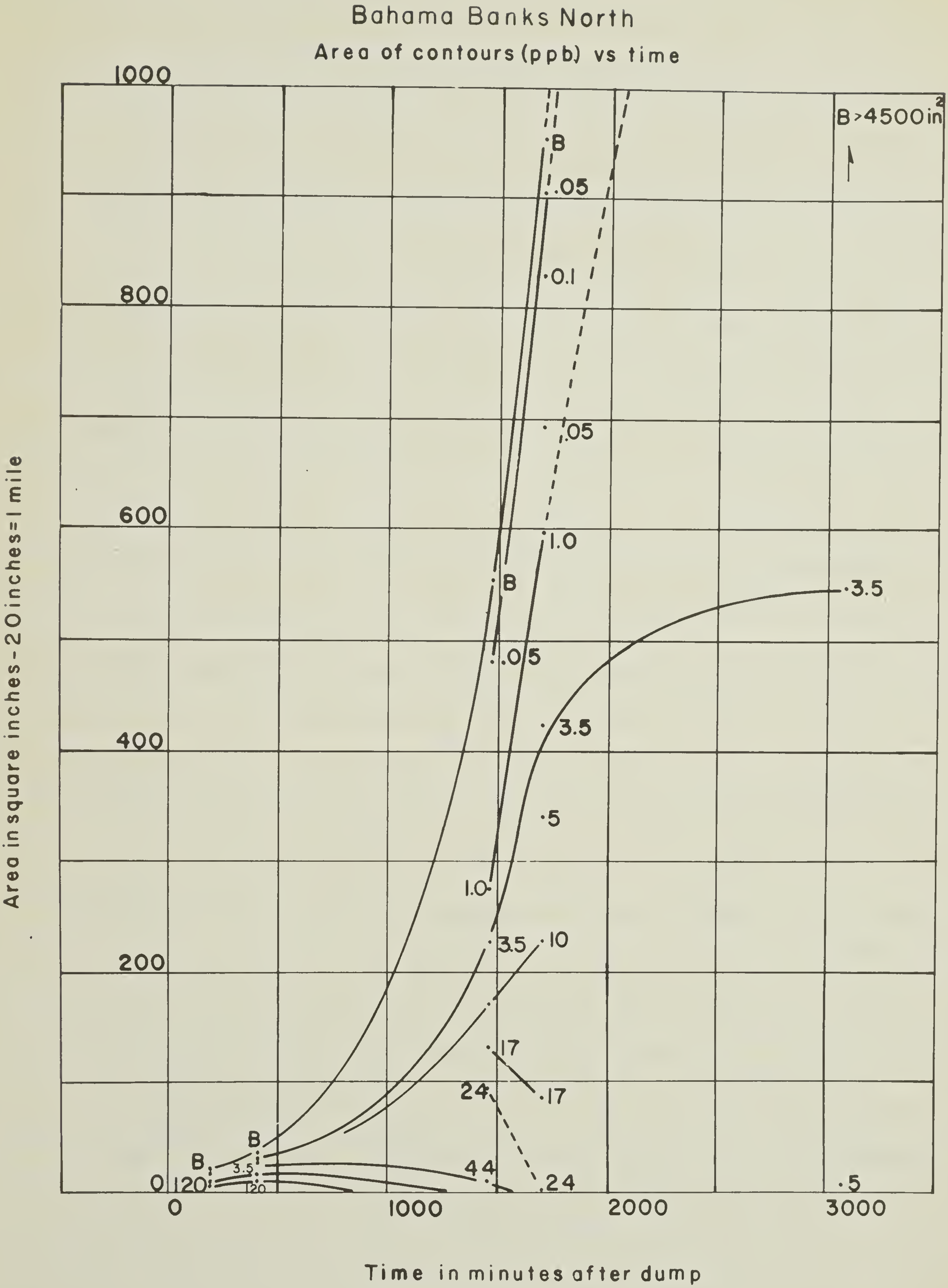

Bahama Banks North
Area of contours (ppb) vs time
B>4500in^2
B
.05
0.1
.05
1.0
B
3.5
.05
3.5
5
1.0
3.5
10
17
17
24
24
44
B
B
3.5
120
120
5
0
1000
800
600
400
200
0
1000
2000
3000
Area in square inches - 20 inches = 1 mile
Time in minutes after dump

FIGURE 16

Bahama Banks South

Area of contours (ppb.) vs time

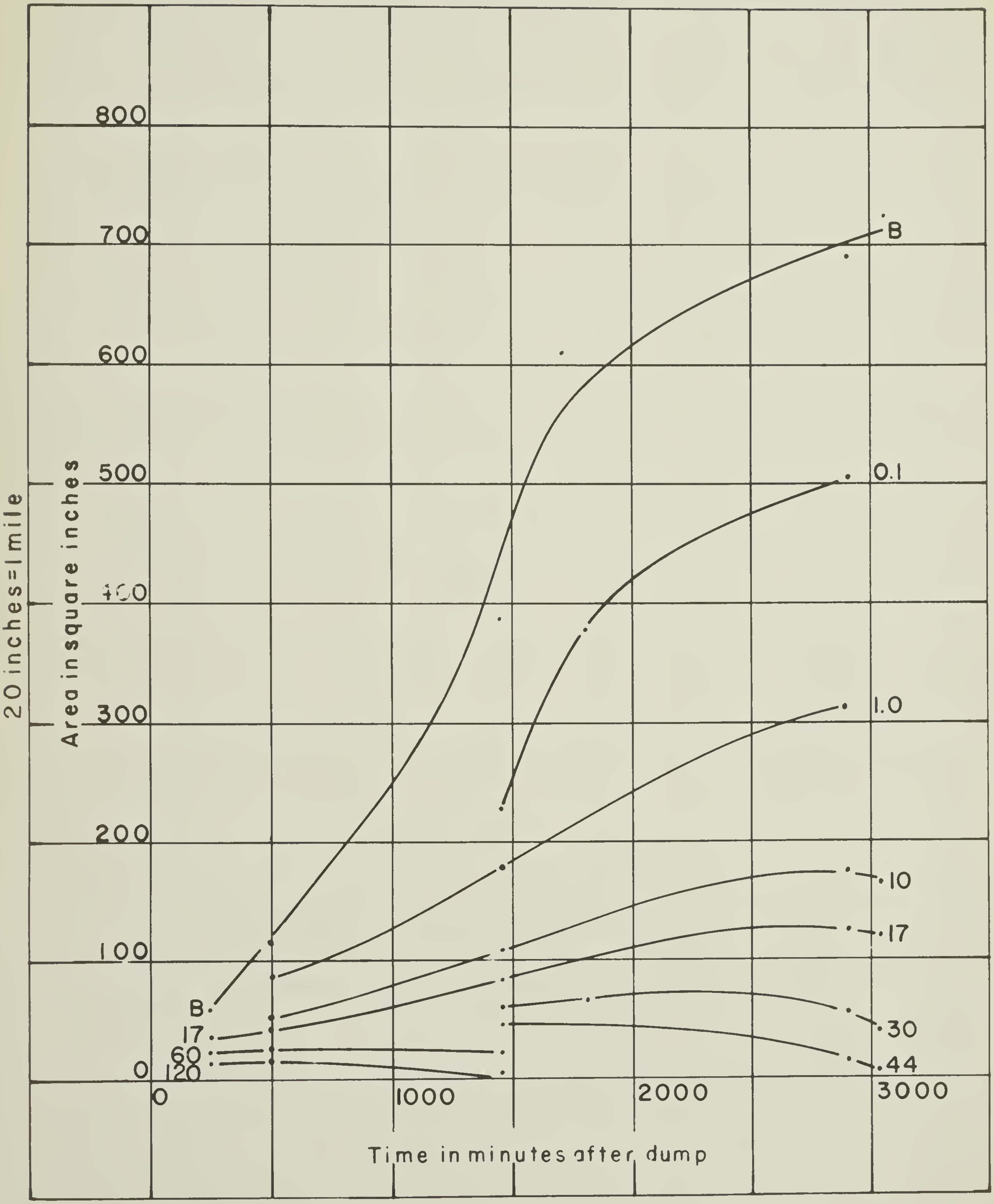


FIGURE 17

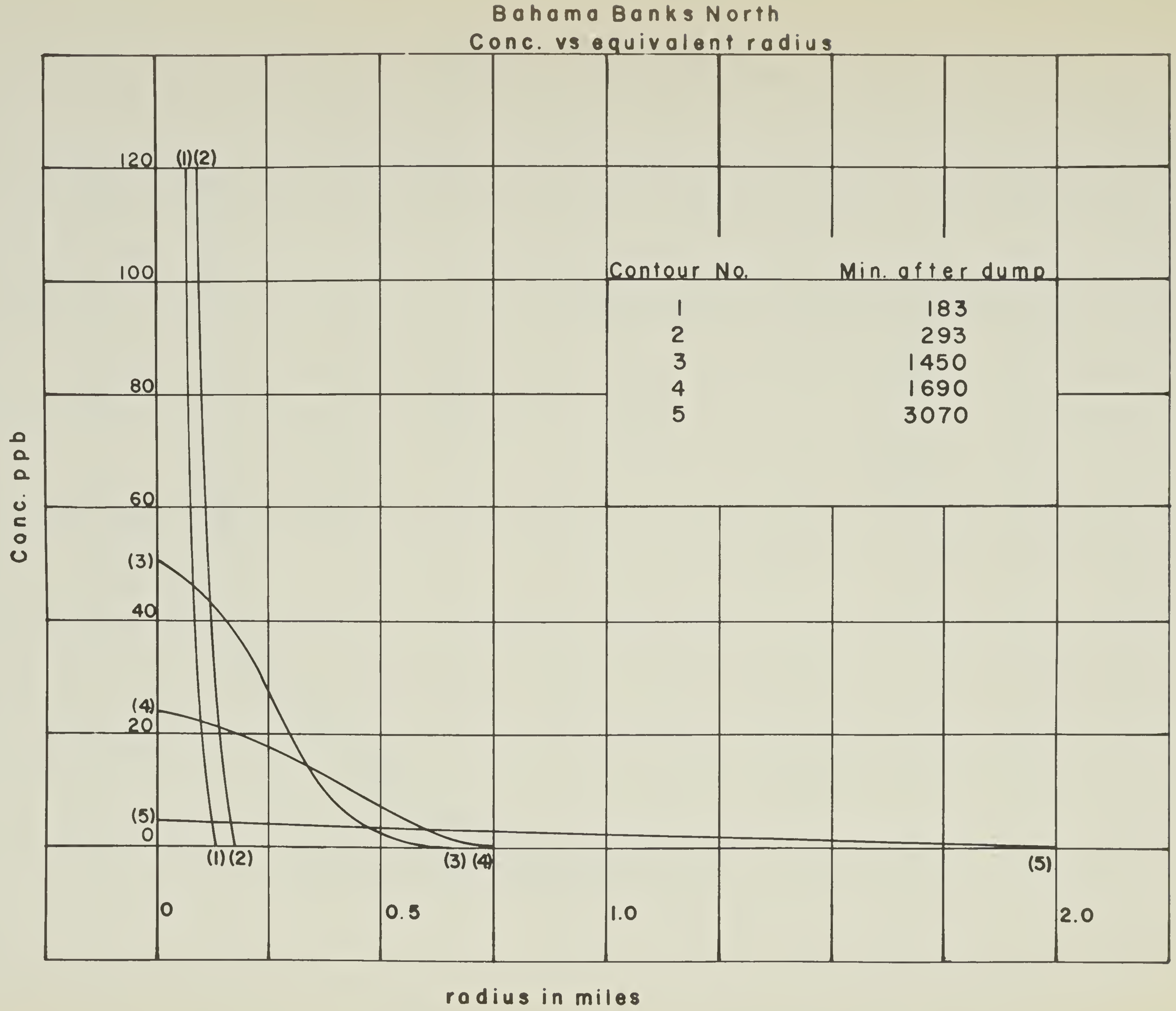

Bahama Banks North
Conc. vs equivalent radius
Conc. ppb
120
100
80
60
40
20
0
(1)(2)
(3)
(4)
(5)
(1) (2)
(3) (4)
(5)
0
0.5
1.0
2.0
radius in miles
Contour No.
Min. after dump
1
183
2
293
3
1450
4
1690
5
3070

FIGURE 18

Bahama Banks South
Conc. vs equivalent radius

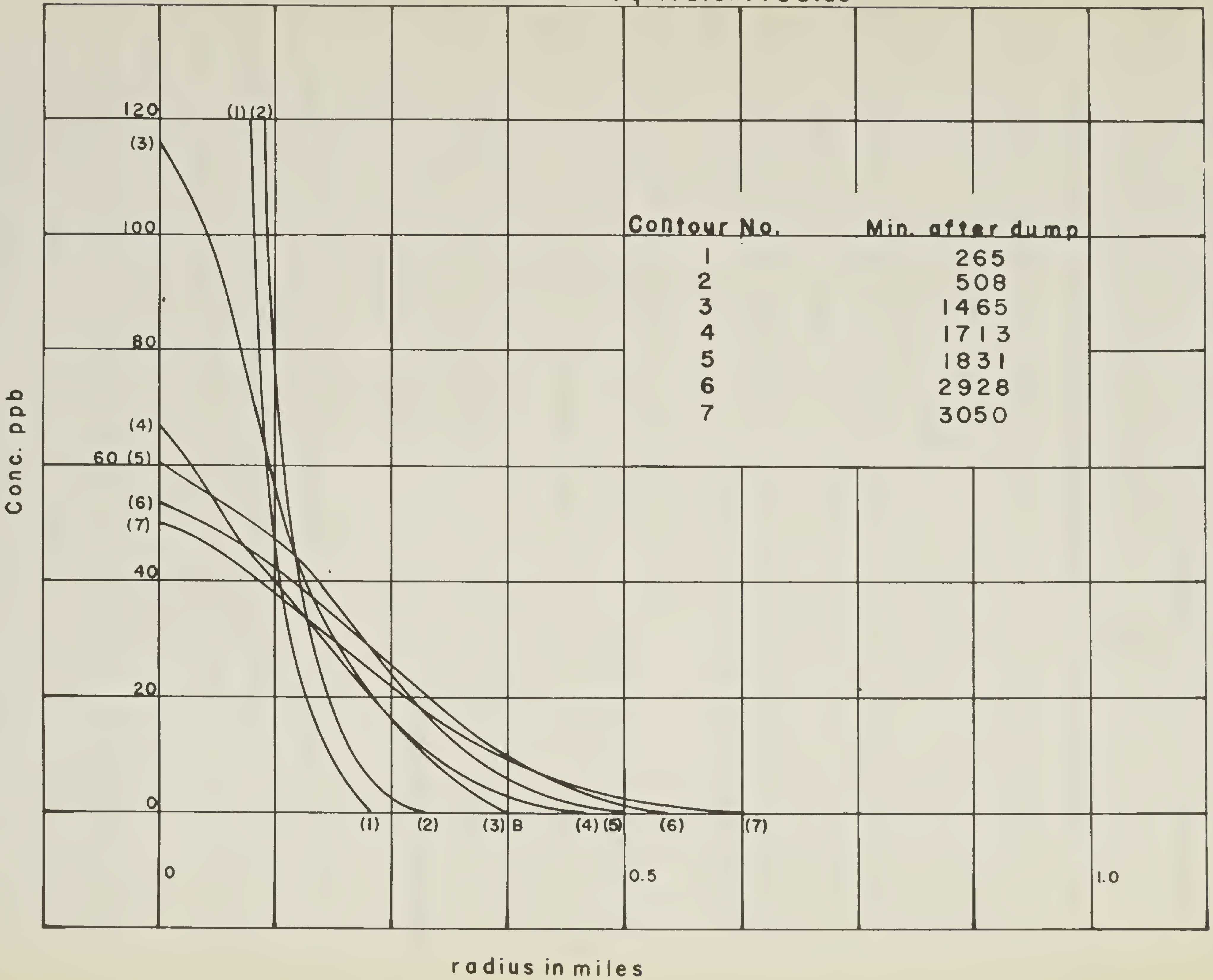


FIGURE 1 9

the coast of New Jersey than on the Bahama Banks.

Smith (1940) reports that, if the wind drift observed in December 1939 were to prevail for a given length of time, it would take at least two months for a water mass to drift from the Florida Channel to the shore of Andros Island. When the center of high concentration is designated as the identifying tag of the dyed water, drifts of the same order of magnitude are observed. Taking into consideration the apparent increase of tidal velocities near the edge of the bank, we estimate that under conditions of steady southeasterly winds (3 to 5 knots), it would take 10 to 12 days for a water mass near Russell Beacon to reach the edge of the bank, and in excess of 40 to 45 days for water near the position of BBS to arrive at the same destination. As the winds are regularly shifting, it is apparent that a body of water may be shifted to and fro for long periods of time without making much headway in any one direction.

If the expanding outline of the dye patch is regarded as the perimeter of the original water mass, and the leading edge of the patch is projected through time, it is estimated that, under the prevailing wind conditions, some of the dyed water at Russell Beacon would reach the edge of the bank in 6 to 8 days, and the water of BBS in 20 to 25 days, or roughly in half the time for advective motion alone.

The general motion of a tracer particle may be simply described by a combination of the velocity of the mean flow and some diffusion velocity, as P. The relative importance of P can be described by the dimensionless ratio of the mean flow to P. As this ratio increases, the contribution of turbulence becomes less and less important in the overall displacement of a particle. Computation of this ratio from average current velocities and P gives values of 75 (BBS), 50 (BBN), and a set of values from 30 to 40 for the New Jersey experiments. These general trends indicate that the contribution of turbulence to the overall displacement

of a tracer particle is more significant off the coast of New Jersey than in the shallow waters of the Bahama Banks.

ACKNOWLEDGMENTS

Thanks are due to Dr. John Imbrie, who has worked extensively on carbonate problems in the Bahamas and who suggested this area for our study. R. Gerard set up the field program, and B. Katz carried out the aerial photography work. P. Breland participated in the shipboard program and carried out many of the instrumentation tasks. Dr. T. Ichiye gave valuable advice in the interpretation of the data. This work was supported by the Atomic Energy Commission of the U. S. Government under Contract AT(30-1)2663.

FIGURES AND TABLES

Figures

1. Location of dye dumps on Great Bahama Bank, August 1962.

2. Motion of dye patch, BBN, August 10 through 12.

3. Dye contour #1 and 2, BBN, 3.06 and 6.61 hours after dump.

4. Dye contour #3, BBN, 24.12 hours after dump.

5. Dye contour #5, BBN, 51.2 hours after dump.

6. Aerial photograph, BBN, 25 hours after dump.

7. Motion of dye patch, BBS, August 13 through 15.

8. Dye contour, BBS #1, 4.56 hours after dump.

9. Dye contour, BBS #3, 24.4 hours after dump.

10. Dye contour, BBS #6, 48.8 hours after dump.

11. Dye contour, BBS #7, 50.9 hours after dump.

12. Aerial photograph, BBS, 1.83 hours after dump.

13. Aerial photograph, BBS, 31 hours after dump.

14. Graph of length of long and short axes of the dye patches versus time.

15. Graph of maximum concentration versus time for the Bahama experiments.

16. Graph of area of contours (ppb) versus time, BBN.

17. Graph of area of contours (ppb) versus time, BBS.

18. Graph of concentration versus equivalent radius, BBN.

19. Graph of concentration versus equivalent radius, BBS.

Table

I. Areas in square miles enclosed by contour of threshold concentration.

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